PILOT AUTHORITY AND AIRCRAFT PROTECTIONS

Air Line Pilots Association

Airworthiness Performance Evaluation and Certification Committee

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CONTENTS

1.0 INTRODUCTION

Modern airliners are equipped with many systems designed to protect the aircraft and its occupants from harm. These systems range from simple warning devices to complex envelope protections. The modern Fly-By-Wire (FBW) flight control system with their flight envelope protection features have the potential of offering significant safety benefits over the protection features of aircraft with conventional flight control systems.

The addition of various protection systems has tended to improve airline accident rates over the years[1]. Occasionally however, some of the very systems designed to protect the aircraft have contributed to accidents. This opposite effect of the onboard safety systems seems to be the result of inadequate or incomplete design, or the occurrence of unanticipated events. In those cases where the safety system itself was causal to an accident, the flight crew was often unable to counter the effects of the system.

This paper presents a discussion of the evolution of aircraft protection schemes and lessons learned, along with design recommendations for aircraft systems.

2.0 ARGUMENT

Aircraft protection systems should be designed so that the aircraft is fully protected without limiting pilot authority. However, pilot authority does not necessarily mean that the pilot has the ability to select an inappropriate system configuration or operate the flight controls so as to jeopardize the structural integrity of the aircraft. Rather, the pilot in command must have the authority to obtain maximum available system and aircraft performance, in conjunction with safe operation of the aircraft, under all flight conditions.

Aircraft protection systems should be designed to allow pilots easy access to the normal operating envelope of the aircraft and its systems. A straightforward and intuitive disengagement scheme must always be available to allow the pilot increased control authority, up to structural or aerodynamic limits in an emergency situation.

3.0 ON-GROUND SENSING

An example of an early protection system is the on ground sensing function provided by squat switches. Early squat switch systems retained full pilot authority by providing full pilot override. Aircraft on-ground sensing systems are an example of a protection system that can either limit or retain full pilot authority, depending upon their design.

On-ground sensing was provided in earlier designs, many of which are still in service, by squat switches whose purpose was to prevent inadvertent activation of ground spoilers and engine

[1] The Impact of Automation on Accident Risk, Airbus Industrie, 14 September, 1998.

reverse thrust. In cases where the squat switch did not properly sense ground contact the pilot still could manually deploy speed brakes and over-ride the inhibitions against reverse thrust.

Subsequent designs of ground sensing systems began to limit pilot authority. The thought was, if we can prevent the pilot from activating a system at the wrong time, pilot error can be prevented. Actually, pilot error may just be supplanted by design error. Preventing a pilot from over-riding a system, supposes that the designer has evaluated all possible contingencies, and that the designer's judgement over the situation, is superior to the pilot's.

On-ground sensing designs that limit pilot authority can have disastrous consequences. An example of this can be seen in an early A-320 design. In a particular case that was not envisioned by the designer, the aircraft in this example (an Airbus A-320) landed on a wet runway, during very adverse conditions, and commenced to hydroplane. There was insufficient weight on the wheels to trigger the aircraft on-ground logic (weight on both wheels was required). Reverse thrust was locked out. Because the aircraft had not transitioned to the ground mode, no deceleration systems were available. The aircraft eventually slowed enough to place sufficient weight on the landing gear olio that allowed the deceleration devices to become available. Unfortunately, valuable time was lost and the aircraft was not able to stop on the available runway.

The most compelling argument for manual over-ride is the fact that all possible contingencies can never be totally predicted.

This system has now been modified to allow a slight extension of the speed brakes when only one wheel senses weight to more firmly place the aircraft weight on the wheels allowing full activation of the ground sensing system. This should prevent a reoccurrence of this type of accident. Although there is still no manual over-ride of the system, the report issued regarding this accident, called for **additional pilot authority** through the following recommendation[2]:

> *Possibility should be analyzed to introduce the emergency use of ground spoilers and thrust reversers independently of meeting the criteria imposed by aircraft logics.*

3.1 Recommendation

To maintain pilot authority over a malfunctioning on-ground sensing system, a method to over-ride the system by the pilot must be provided

4.0 STALL PROTECTION

[2] Report on the Accident to Airbus A320-211 Aircraft in Warsaw on 14 September 1993. Page 45.

Stall protection is another example of a protection system that could have disastrous results if full pilot authority is not maintained. This basic protection scheme often involves the use of a stick pusher. Most modern aircraft that use stick pushers provide for the crew to manually deselect the system. Earlier designs do not always provide this capability. Without pilots having the authority to disable the system, crews were forced to hold excessive amounts of backpressure to counteract a malfunctioning system.

Obviously, stall warning and stall prevention systems are very important and aircraft that use stick pushers do so for stall warning and because of undesirable stall characteristics. The most extensive over-ride capability is provided by the Embraer EMB-145, where a single push button on the yoke disables or disengages the stick pusher, the auto-pilot, and the elevator trim system. The Canadair CRJ has a toggle switch next to the captain's knee that can be used to deselect the stick pusher. Since the pilot has the ultimate responsibility for the safe conduct of the flight, the ability to over-ride a malfunctioning system is of utmost importance

4.1 Recommendation

To maintain pilot authority over a malfunctioning stall warning/protection system, a method of over-riding the system must be provided.

5.0 ENGINE CONTROLS

In general, Full Authority Digital Engine Controls (FADEC) systems provide engine protection but sometimes limit pilot authority. The ability to aggressively command engine thrust provides a level of aircraft protection while retaining a high degree of pilot authority. Typical FADEC systems allow the pilot, in an emergency, to simply slam the throttle full forward and receive the maximum allowable thrust (note the word "allowable, not "available"). Maximum allowable means the maximum thrust for existing conditions programmed into the FADEC by aircraft/engine designers. Maximum thrust can be the maximum certified, but could be the minimum certified thrust and might be the thrust setting allowed to meet engine warranty provisions. This has become a standard design feature of FADEC controlled engines.

Some designs have limited pilot authority by limiting allowable thrust to less than available thrust. At least one operator of the Airbus A319 (not the manufacturer) has elected to limit the thrust allowable to the pilot to 22,000 pounds per engine. The aircraft is **certified** to 23,500 pounds thrust per engine, an additional 6.8% per engine. The engines are actually capable of producing 30,000 pounds of thrust each. That means that there is available in the engine, but not to the pilot, an extra 20% of engine thrust. Full rated engine thrust however, may not be desirable. In the case of the A319, high thrust settings under certain conditions can generate problems with Vmc, adverse pitching moments and elevator authority. However, for most designs, an aircraft can accommodate a 30% increase in thrust (over the base design), without adverse effects.[3]

Reduced thrust settings provided by FADEC systems are appropriate for routine line operations. However, the inability of the pilot to access full certified thrust when needed to recover from a wind shear encounter, an event where full performance is needed, or other emergency events requiring additional thrust may spell disaster for all aircraft occupants. If there were to be an accident where it could be shown that the extra 6.8% of thrust would have made a difference, the tort lawyers would have a strong case for a negligent design or operator decision. The current operational reasons to limit the thrust available to the pilot are to reduce fuel burn and increase engine life. FADEC systems can be programmed to force the pilot to make a reduced thrust takeoff on every event, despite conditions that may warrant otherwise. This decision was not made with the concurrence of the pilot in command. The pilot is not allowed to select maximum certified thrust (the thrust level that the manufacturer thought was appropriate for the aircraft at that weight) to achieve a higher level of safety for a takeoff with clutter, to have greater obstacle clearance capability or better performance in case of wind shear.

The Boeing 777-200 also limits pilot authority in a similar manner. One of the three available engines, the Pratt & Whitney 4000, is rated to produce between 74,500 and 84,600 pounds of thrust. The customer specifies the desired thrust level (74,000, 77,000, or 84,000), and this is then pin selected on the FADEC and marked on the engine data plate. On heavy weight versions of the 777, the thrust is set at the higher level. The lower thrust is used for the lighter weight versions, but the crew is not allowed to access the higher thrust capability of the engine, even in an emergency.

But not all designers have agreed with this limitation to pilot authority. For example, the McDonnell Douglas designed MD-90 allows the pilot to select an emergency thrust level by pushing the throttles through a brake bar. Many MD-90s are equipped with IAE V2500 engines rated at either 25,000 or 28,000 pounds of thrust per engine (customer option). However, the V2500 engine is capable of over 30,000 pounds of thrust. By pushing through the gate on the MD-90 throttle quadrant, the pilot is able to select full rated N1 thrust of over 30,000 pounds with full engine overspeed protection (both N1 and N2). This extra thrust is provided to the pilot on the occasion that the pilot determines it is needed to counter wind shear or otherwise escape ground contact.

Philosophically, the design team at McDonnell Douglas felt that they could not justify a scenario which saw the aircraft impacting the terrain with both engines only producing 25,000 pounds of thrust, when the engines were capable of over 6,000 more pounds of thrust, with full overspeed protection (Note: there may be other factors to limit the max thrust such as Vmc considerations.).

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[3] ALPA-Airbus meeting April 1998.

Yet another case for full pilot authority is found in the MD-90 thrust reverser development. The MD-90 initially limited the amount of reverse thrust available to the pilot based upon airspeed. This was done to reduce engine damage at low airspeeds due to FOD and also for a rudder power consideration single engine. Unfortunately, it also prevented the pilot from utilizing an emergency source of stopping power, such as might be needed on an icy ramp. Fortunately, the manufacturer changed this design (suggested by ALPA) to provide the pilot with full reverse power, if required. Full emergency reverse (full rated N1) is provided if the pilot pulls the reverse lever through the aft reverse detent.

5.1 Effects Of Additional Thrust On Climb Performance

Additional thrust can have a significant impact on climb rates. The basic equation to calculate the climb rate that results for the additional thrust is presented in equation 5.1.

$$dh/dt = V\sin\gamma = V(T - D)/W$$

dh/dt = climb rate
V = velocity
sinγ = climb angle
T = thrust
D = drag
W = aircraft weight

Equation 5.1

The equation can be simplified such that the increased rate of climb capability (Δdh/dt) can be determined for various amounts of increased thrust (ΔT). Using this equation, the following tables can be developed (note: V_2 = takeoff safety speed, and Vapp = approach speed). These tables depict some climb rate values for various thrust conditions and aircraft. The two-engine climb rate column depicts the additional climb capability that is provided by the additional thrust for such uses as obstacle clearance or wind shear recovery capability. The single engine climb capability column lists the additional capability that is available in the engine out situation. As can be seen in the following table, the change in climb rate can be significant.

Flight Condition	Weight (Pounds)	Speed (Knots)	Δ Thrust (Pounds) 2 Engine/ 1 Engine	Δ Climb Rate 2 Engine (Feet/Min)	Δ Climb Rate 1 Engine (Feet/Min)
Take Off	150,000	$V_2 = 151$	3,000/1,500	306	153
Go Around	130,000	$V_{app} = 123$	3,000/1,500	288	144

AIRBUS A-319
ADDITIONAL THRUST CAPABILITY
Table 5.1

Flight Condition	Weight (Pounds)	Speed (Knots)	Δ Thrust (Pounds) 2 Engine/ 1 Engine	Δ Climb Rate 2 Engine (Feet/Min)	Δ Climb Rate 1 Engine (Feet/Min)
Take Off	500,000	$V_2 = 158$	22,000/11,000	704	352
Go Around	400,000	$V_{app} = 131$	22,000/11,000	729	364

BOEING 777
ADDITIONAL THRUST CAPABILITY
Table 5.2

5.2 The Effects Of Additional Thrust Capability On CFIT Recovery Capability

A CFIT escape maneuver is a procedure designed to remove an aircraft from a pending terrain contact as judiciously as possible. This maneuver is designed to protect the aircraft, while demanding maximum performance. Typically, the aircraft is in a descent, and upon receiving a terrain warning, the pitch is increased to a value between 15 to 20 degrees nose up, until the stick shaker or maximum AOA (angle of attack) is reached. This maneuver can be initiated anywhere from a clean cruise descent (280 to 300 KIAS), or fully configured at approach speed.

The increased thrust capability translates to increased climb performance, which translates to decreased exposure the terrain threat during the recovery procedure. FADEC systems designed to limit the ability of the pilot to select maximum thrust available therefore degrade the ability of the pilot to recover from CFIT incidents. The increased climb capability is presented in the following tables.

Flight Condition	Weight (Pounds)	Speed (Knots)	Δ Thrust (Pounds) 2 Engine	Δ CFIT Climb Rate (Feet/Min)
CFIT Escape On Descent	130,000	280	3,000	655

AIRBUS A-319
ADDITIONAL THRUST CAPABILITY
Table 5.3

Flight Condition	Weight (Pounds)	Speed (Knots)	Δ Thrust (Pounds) 2 Engine	Δ CFIT Climb Rate (Feet/Min)
CFIT Escape On Descent	400,000	300	22,000	1673

BOEING 777
ADDITIONAL THRUST CAPABILITY
Table 5.4

5.3 The Effect Of Additional Thrust On Recovery From Windshear

Wind shear is defined as a change in wind speed and/or wind direction in a short distance resulting in a tearing or shearing effect. It can exist in a horizontal or vertical direction and occasionally in both.[4]

Microbursts contribute to wind shear and are small-scale intense downdrafts, which, on reaching the surface, spread outward in all directions from the downdraft center. This causes the presence of both vertical and horizontal wind shears that can be extremely hazardous to all types and categories of aircraft, especially at low altitudes. Due to their small size, short life span, and the fact that they can occur over areas without surface precipitation, microbursts are not easily detectable using conventional weather radar or wind shear alert systems.

Microburst wind shear may create a severe hazard for aircraft within 1,000 feet of the ground, particularly during the approach to landing and landing and takeoff phases. Aircraft may encounter a headwind (performance increasing) followed by a downdraft and tailwind (both performance decreasing), possibly resulting in terrain impact.[5]

Wind shear recovery techniques require that an aircraft maximize and maintain energy while attempting to fly through and/or out of the shear. One of the key elements of enhancing or maintaining aircraft energy is the ability to select maximum available thrust. Engine control designs that limit the pilot's ability to obtain maximum available engine thrust limit the pilot's ability to safely recover the aircraft from a wind shear event. If increased thrust is available in the engine, it should be made available to the pilot. As wind shear is a random event a direct correlation between events is not possible, but in the aggregate, extra thrust increases the aircraft's ability to avoid ground contact in the event of wind shear (See Appendix A).

[4] Airman's Information Manual para 7-1-21.
[5] Airman's Information Manual para 7-1-23. MICROBURSTS

5.3.1 The Effects of Additional Thrust in Windshear Recovery for the Airbus A- 320 (Takeoff)

This test was conducted as an evaluation of the effects of two different engine models on the performance of the A-320 during the takeoff event with windshear. Of interest was the performance in respect to altitude loss, airspeed decay, and time to climb out of the windshear area. The two different engine models were the PW 2522 engine and the PW 2524 engine.

The data at attachment three shows the positive effect of extra thrust during windshear recoveries. On average, the aircraft will lose 100ft less, 13KIAS, and spend approximately the same time in the windshear event (0.5 sec delta). As windshear is a random event a direct correlation between each event is not possible but in the aggregate extra thrust increases the aircraft's ability to avoid ground contact in the event of windshear. Increased thrust also reduced the amount of time the aircraft was exposed to the low altitude windshear event. This reduction in time enables the aircraft to gain altitude quicker and thus avoid ground impact.

The amount of difference between the two engine models in recovery altitude and airspeed loss is on the order of 20% of the total loss. The difference between the engine thrust output is on the order of 10%. Thus a small increase in thrust results in a doubling of the safety margin. If increased thrust is available it should be used to increase the safety margin. If the aircraft is structurally able to have an increased thrust engine it should be installed. If the reduced thrust option is desired for cruise cost reasons the pilot should be able to select the higher thrust in an emergency situation. An increase in 20% in the safety margin prior to ground impact is an obvious benefit.

5.3.2 The Effects of Additional Thrust in Windshear Recovery for the Boeing B-777 (Takeoff)

This test was conducted as an evaluation of the effects of two different engine models on the performance of the B-777 during the takeoff event with windshear. Of interest was the performance in respect to altitude loss, airspeed decay, and time to climb out of the windshear area with the PW 4000 engine (74000 lbs thrust) and the PW 4084 engine (90000 lbs thrust).

During the windshear model 4 events the PW 4000 engine configuration had on average a 380 ft altitude loss, an airspeed loss of 55 KIAS, and spent 13.5 seconds in the event. The PW 4084 engine configuration had an average 200 ft loss, an airspeed loss of 51 KIAS, and spent 12.5 seconds in the event. For this windshear model, a 21% increase in thrust resulted in an almost 100 % increase in performance

During the windshear model 2 event the PW 4000 engine configuration had a 36 KIAS loss and spent 15.5 seconds in the event. The PW 4084 engine configuration had a 34 KIAS loss and spent 11.0 seconds in the event.

5.3.3 The Effects of Additional Thrust in Windshear Recovery for the Boeing B-777 (Approach)

This test was conducted as an evaluation of the effects of two different engine models on the performance of the B-777 during windshear recoveries on approach. Of interest was the performance in respect to altitude loss with the PW 4000 engine (74000 lbs thrust) and the PW 4084 engine (90000 lbs thrust).

On average the PW 4074 (74,000 pounds thrust) engine configuration had a 233 ft altitude loss with a min airspeed of 97 KIAS during the recovery. The PW 4084 engine (90,000 pounds thrust) had a 185 ft loss with a minimum airspeed of 100 KIAS.

The test results show the positive effects of additional thrust during wind shear recoveries. On average, the aircraft will loose 60 ft less.

5.4 Conclusion

Pilot authority to manage engine thrust to the maximum attainable level when required by emergency circumstances must be provided. Reduction of the maximum attainable engine thrust by FADEC systems must not be made for merely economic considerations. Although routine or normal maximum available thrust may be set to a particular predetermined lower value for operational considerations, a method to over-ride this restriction and obtain maximum thrust available, consistent with aerodynamic and controllability issues, must be provided.

6.0 FLIGHT ENVELOPE PROTECTIONS

The design goal of flight envelope protections is to protect the pilot and the aircraft from exceeding the structural or aerodynamic flight envelope. The protection features afforded by FBW designs allow the pilot an enhanced ability to aggressively maneuver the aircraft, without fear of exceeding the flight envelope. Additionally, performance margins with respect to gross weight, c.g., and wing configuration can be maintained. This ability to safely and aggressively maneuver the aircraft enhances pilot capability to control the flight path and performance of the aircraft.

It is assumed that the primary reason for a flight envelope exceedance is human error. As Dr. Billings states in his book, Aviation Automation, it is a myth to think that you can design out human error[6]. [Myth 2: Technology can help us supplant the unreliable human.]. You may attempt to design out pilot error, but you may inadvertently replace it with designer error.

[6] Billings, Aviation Automation. Page 53

6.1 Design Error

Design error can become a factor when the pilot is limited to the designer's perception of the safe flight envelope. Preventing the pilot from exercising ultimate control supposes that **all possible contingencies in all possible environments** have been correctly and adequately addressed. The danger of this philosophy was recently demonstrated when all cockpit displays were temporarily lost during an aircraft upset In designing the A300, Airbus developed a complex roll rate-of-change monitor that triggers the reset and self-test function if that rate of change exceeds 40 degrees/sec. The design assumption was that no A300 in normal or emergency operations would exceed that trigger rate.[7]

6.2 Flight Envelope Protection Design Philosophies

Currently, there are three types of flight control systems used in commercial transport aircraft. The first and most prevalent is the conventional hydraulic/mechanical flight control system. The next two are both fly-by-wire (FBW) flight control systems, each incorporating a different design philosophy to limit the flight envelops.

6.2.1 Conventional Flight Envelope Protections

Aircraft with conventional flight control systems use a number of aural, visual, and tactile systems to warn the pilot of actual or pending flight envelope exceedances. Except for the case of some stick pusher designs, these systems can be ignored or over-ridden by the pilot. This design is perceived as offering the pilot the ultimate in control, although aircraft protection features are at a minimum.

Aircraft in the past have been designed with a set of "normal" limits which have a buffer to the "never exceed limits" to allow for the inevitable lack of precision which can cause an overshoot of the normal limits.

6.2.2 Hard Flight Envelope Protections

Airbus incorporates "hard" limits in the design of their FBW flight control system. Hard limits prevent the pilot from exceeding the flight envelope of the aircraft. That is, the aircraft is not allowed to be stalled, over-banked, over-stressed, or over-sped. In other words, the designed aircraft envelope is maintained and protected.

6.2.3 Soft Flight Envelope Protections

Boeing incorporates "soft" limits in the design of their FBW flight control system. Soft limits "suggest" and warn when a limit is being approached by increased control feel (stick forces)

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[7] NTSB Warns of Display Reset Problem, Aviation Week and Space Technology, Feb. 9, p.76

and by introducing aural and visual warnings. With soft limits the pilot is warned, but then allowed to stall, over-bank, over-stress or over-speed the aircraft, if necessary or desired.
Sensor malfunctions may make a case for soft limits or at least pilot overrides. On the surface it would seem that preventing the pilot from stalling the aircraft, is a desirable function of a protection system. However, there have been cases of multiple sensor malfunctions (lightening strikes welding both AOA vanes[8]), where incorrect information was passed to the aircraft fight computer. These malfunctions have resulted in false stall warnings. If the pilot in command is unable to over-ride a malfunctioning system, in this case a stall warning system (it could be any system however), aircraft control may be lost. When a warning system can not be over-ridden, the warning system is now in command of the aircraft. A false stall warning could result in the pilot not being able to select a slow enough speed to effect a safe landing.

6.2.4 Flight Envelope Protection Overrides

Even with the soft protection features on the FBW Boeing 777, the Primary Flight Computers can be shut off by the activation of a guarded switch on the overhead panel. This places the flight control system in a direct inceptor to control surface activation mode. There is no similar provision in the Airbus FBW design to readily place the aircraft in the direct mode.

The soft flight control limits in the Boeing FBW design are implemented in part by increased control forces on the yoke. This design philosophy allows both protection and ease of override when necessary. Some unpublished Boeing and Calspan research suggests that force limit, or the ramp-up of force gradients, do not work well on small displacement controllers to implement a soft protection scheme. Airbus may have had no choice but to go with hard limits on their side stick design.

6.2.5 Flight Envelope Authority

In addition to the design questions, there is also a philosophical question that needs attention. That question regards FAR 91.3, which states, "The pilot in command of an aircraft is directly responsible for, and is the final authority as to, the operation of that aircraft." As Dr. Billings states in his book, "Does a pilot whose control authority is limited by software encoded in the flight control computer have full authority to do whatever is necessary to avoid an imminent collision, or ground contact? An editorial in Flight International ("Hard limits, soft options," 1990) states:

> *"There is, however, another approach available: to develop a "softer" fly-by-wire system which allows the aircraft to go to higher limits than before but with a progressive degradation of flying qualities as those higher limits are approached. It is this latter philosophy which was adopted by the Soviets with fighters like the MiG-29 and Sukhoi Su-27. It is not, as Mikoyan's chief test*

[8] Personal conversation, John Cashman, Director, Boeing Flight Test,

pilot…admits, "necessarily a philosophy which an air force will prefer, however: Although this….approach requires greater efforts…it guarantees a significant increase in the overall quality of the aircraft-pilot combination. This method also allows a pilot to use his intellect and initiative to their fullest extent."

The American counterpart, the F-16, was designed with "hard" limits. The original General Dynamics flight envelope algorithms did not predict a deep stall mode later encountered in flight. Therefore the design of the FBW flight control system did not allow for sufficient flight control authority necessary for pilot recovery from the deep stall mode. This necessitated the last pilot option - ejection from the aircraft. Subsequently a system for manual over-ride of the flight control computer has been incorporated.

Fighter aircraft are designed with flight control systems requiring near linear inputs yielding controlled and predictable flight characteristics up to the edge of their design envelope. Fuel considerations, freight and optimal passenger load considerations often dictate that commercial transport aircraft likewise operate near their design limits. In commercial transport aviation, the edge of the envelope is also often approached during high altitude flight where the spread between low speed and high-speed buffet is at a minimum. In the early days of aviation, this was referred to as the "coffin corner."

As Dr. Billings states in his book: "Although civil aircraft do not face the threat posed to a fighter aircraft under attack, if its maneuverability is limited, their pilots do on occasion have to take violent or corrective action, and they may on rare occasions need control or power authority up to (or even beyond) normal structural and engine limits to cope with very serious problems. [9]" The issue is whether the pilot, who is legally, morally and ultimately responsible for safe mission completion should be permitted to operate up to or even beyond airplane limits, when he or she determines that a dire emergency requires such operation.

To illustrate the interrelation of protection features and pilot authority, two maneuvers critical to the safety of flight, where the differences between a conventional and a FBW aircraft design protection features are the most pronounced, will be discussed. The first maneuver is the Controlled Flight into Terrain or CFIT avoidance maneuver. The second is the high speed upset recovery where a recovery "g" greater than the design limit of 2.5 "gs," becomes a factor.

6.3 Controlled Flight Into Terrain (CFIT)

Controlled Flight into Terrain (CFIT) is the leading causes of fatal aviation accidents.[10]

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[9] China Airlines, B747-SP, 2/19/1985, 300 miles NW of San Francisco.
[10] CFIT Training Aid, section 3 page 3.3.

6.3.1 Flight Test

A test program was developed (full test report presented in Appendix B) to compare the CFIT maneuver performance capabilities of aircraft with hard versus soft Fly-By-Wire (FBW) flight control systems. To obtain this data, simulated CFIT avoidance maneuvers utilizing a Boeing 777-300 and an Airbus A330-200 were performed. These tests were performed at the Boeing Flight Test Facility in Seattle, Washington and the Airbus Flight Test Facility at Toulouse, France.

This flight test had a two-fold purpose. The first was to evaluate the effectiveness and appropriateness of a recovery technique that was developed for convention aircraft without regard for the flight envelope protections incorporated in modern FBW aircraft. The second purpose was to develop and/or evaluate CFIT escape maneuvers that utilize the maximum capability of the aircraft afforded by the protections incorporated in their respective FBW flight control systems.

6.3.2 CFIT Maneuver

A CFIT escape maneuver is a procedure designed to remove an aircraft from a pending terrain contact as judiciously as possible. This maneuver is designed to protect the aircraft, while demanding maximum performance. Typically, the aircraft is in a descent, and upon receiving a terrain warning, the pitch is increased to a value between 15 to 20 degrees nose up, until the stick shaker or maximum AOA (angle of attack) is reached. This maneuver can be initiated anywhere from a clean cruise descent (280 to 300 KIAS), or fully configured at approach speed.

Transport aircraft are equipped with a variety of Ground Proximity Warning Systems (GPWS). These systems will usually, depending upon sophistication, warn the flight crew 5 to 60 seconds before impact. The most advanced system is Enhanced GPWS which uses a terrain data base and compares current aircraft position to known terrain hazards stored in an onboard data base. This system can provide a full 60 seconds of warning before terrain impact. However, at the point where a GPWS warning is issued to the flight crew, aircraft performance can become the critical factor. The pilot must have the authority necessary to achieve the maximum obtainable aircraft performance.

6.4 Aircraft Flight Control Design

6.4.1 Aircraft With Conventional Flight Controls

For an aircraft with conventional flight controls only mechanical stops and control forces limit pilot authority. In reality, flight controls have set mechanical limits; that is, the pilot cannot demand an elevator deflection of 90 degrees, and flight control power has definite physical limits. Flight envelope excursions are possible and are typically indicated by the onset of high stick forces or stick shaker activation. The typical CFIT escape maneuver for an aircraft with conventional flight controls, requires the pilot to select TOGA thrust, rotate at a smooth rate of 3 degrees per second (to avoid overstressing or stalling the aircraft) to a pitch attitude of between 15 to 20 degrees nose up. This pitch attitude is maintained until the stick shaker activates or terrain clearance is assured. The stick shaker gives the pilot an indirect indication of optimum AOA and must be respected to effect recovery. Due to speed and thrust changes, with the resultant variable and usually out of trim stick forces; flying the stick shaker activation angle to maintain optimum AOA, can be quite difficult.

The Cali accident report states, "if the pitch attitude had been varied to perfectly maintain the stick shaker activation angle (optimum AOA), the airplane could have been climbing through a position that was 300 feet above the initial impact point.[11]" Cali is an example of a CFIT accident where a FBW design may have made a difference.

6.4.2 FBW Aircraft With "Hard" Protection Features

Airbus incorporates "hard" limits in the design of their FBW flight control system. Hard limits prevent the pilot from exceeding the designed flight envelope of the aircraft. That is, the aircraft may not be stalled, over-banked, over-stressed, or over-sped. In other words, the designed aircraft envelope is maintained and protected.

The Airbus design allows the pilot to obtain, in a repeatable fashion, a consistent level of aircraft performance. However, the pilot may be prevented from obtaining maximum aircraft aerodynamic performance.

The procedure for the CFIT escape maneuver in the Airbus aircraft as recommended by Airbus, is for the pilot to pull full back on the stick and apply TOGA thrust. Speed brakes if extended, will automatically retract.

Control laws either stabilize the AOA at an optimum value or adjust pitch rate to obtain maximum allowed g. With the Airbus CFIT escape maneuver pilots can quickly and easily achieve a repeatable consistent level of performance allowed by the envelope limiting system. This ease of handling might, in certain cases, result in optimum CFIT escape performance, even though full aerodynamic performance may not be achieved.

The argument can be made that pilot authority is limited in the "hard" design by the fact the pilot is prevented from exceeding the limits of the flight envelope. The Airbus design allows the pilot to rapidly obtain maximum allowed aircraft performance to avoid ground contact. However, the pilot is prevented from obtaining all possible aircraft aerodynamic performance. That last bit of available but not attainable performance may be all that is necessary to avoid ground contact.

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[11] Controlled Flight into Terrain, American Airlines flight 965. Aeronautica Civil of the Republic of Columbia. Page 52.

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6.4.3 FBW Aircraft With "Soft" Protection Features

Boeing incorporates "soft" limits in the design of their FBW flight control system. Soft limits "suggest" and warn when a limit is being approached by increased stick forces and by introducing aural and visual warnings. With soft limits the pilot is warned, but then allowed to stall, over-bank, over-stress or over-speed the aircraft, if necessary or desired.
In a CFIT escape maneuver with the 777, the current Boeing recommended procedure is to aggressively apply maximum thrust Roll wings level and rotate to an initial pitch attitude of 20 degrees. Retract speed brakes if extended. In all cases, the pitch attitude that results in intermittent stick shaker or initial buffet is the upper pitch attitude limit. When the flaps are not up or at slow speeds with the flaps up, the pitch limit indicator (PLI) provides a visual reference of the pitch attitude limit. Follow flight director TO/ GA guidance if available.[12]

The addition of the PLI in the Boeing 777 FBW design allows the pilot to easily and consistently achieve the optimal aircraft attitude. On the 777 the pilot directly controls pitch attitude and pitch rate. High pitch rates can be attained by the pilot to quickly and precisely place the aircraft at optimum AOA. Although easier than for conventional aircraft, accurately maintaining the PLI still requires a reasonable degree of pilot technique. If ground contact is imminent the pilot can obtain the full aerodynamic performance of the aircraft. High stick forces are required to pull the aircraft into a stall; but the pilot receives numerous warnings and indications of the pending stall condition. Other than a ramp up of stick force there is no indication that the aircraft's g limit has been reached or exceeded. The authority to obtain maximum g is only limited by the feel system and control power. With this design the pilot is allowed to obtain the maximum aerodynamic capability of the aircraft. Although not explicitly stated in the procedure, Boeing's intent is for the pilot to aggressively (greater than 3 degrees/second) rotate to the initial 20 degree pitch attitude.[13]

It is the committee's opinion that the CFIT recovery capability on the 777 could be enhanced if the aircraft's Primary Flight Computers (PFC) were designed to recognize aggressive pilot inputs as a desire for maximum aircraft performance. The PFCs would then provide maximum pitch rate consistent with AOA or g limits (depending on airspeed). If the resultant aircraft performance is not sufficient, the pilot could then pull to the full aerodynamic capability of the aircraft. Additionally, automatic speed brake retraction, in the event of a go around or CFIT maneuver, should be provided in the 777 design. This system although somewhat complex mechanically, can be implemented since the PFCs will control any undesired pitch excursions.

6.4.4 CFIT Recovery Conclusions/Recommendations

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[12] Boeing 777 Flight Crew Training Manual, 1.26June 01, 1997.
[13] Personal conversation John Cashman Feb 18, 1999.

From the data gathered in the evaluation, there was not a distinct advantage of the B777 soft limits vs the A320/330 hard limits for CFIT recovery for open loop performance. However, closed loop evaluations showed that the pilots could achieve more consistent performance results as well as achieve target pull out parameters more quickly in the A320/330 than the B777. Even with the B777 soft limit features, pilots were able to use abrupt pitch inputs without fear of overstress or stall. Both aircraft types offered better handling during CFIT recoveries than conventional aircraft since the FBW design features allowed the pilot more precise control of pitch rate and g onset rate than with conventional flight controls.

6.4.5 Conclusions

- The A330 full aft stick CFIT recovery vs 3 deg/sec pull gave better and more consistent performance without any increase in risk of exceeding envelope parameters.

- No additional or specific pilot training was necessary to perform the full aft stick recovery technique since the FBW design provides excellent pitch rate and g control as well as excellent envelope protection for stall, overstress, or overspeed. From the data gathered in the evaluation, there was not a distinct advantage of the B777 soft limits vs the A330 hard limits for CFIT recovery open loop performance.

- Closed loop performance showed that the pilots could achieve more consistent performance results as well as achieve target pull out parameters more quickly in the A330 than the B777.

- Flight test results indicated that an aggressive pull up in the B777-300 to a pitch attitude of 17.5 degrees generally yielded better CFIT recovery performance than the recommended 3 deg/sec recovery procedure.

- The evaluation pilots' found that the enhanced flight path control precision and envelope protection features available through FBW design were highly desirable.

- The evaluation team preferred the flight envelope limiting features ("soft limits") of the B777 design to a "hard limit" design. This was a subjective judgement based on the premise that there may be situations unforeseen by the designers where the pilot might need to achieve full aerodynamic capability as opposed to being software/control law limited. Another approach may be to incorporate "hard limits" with a pilot override capability such as an "instinctive cut-out" switch.

6.4.6 Recommendations

- Airbus FBW operators should use the manufacturers recommended full aft stick CFIT recovery procedure. This may seem obvious, but until this report, none of the US operators were following the Airbus recommended procedure. None felt that it was prudent to do so.

- The manufacturer's B777 CFIT recovery procedure should be utilized.
- Future FBW designs should consider
  - ♦ Protected flight envelope limits with
  - ♦ Envelope protections over-ride
- Incorporation of FBW design features is highly desirable in future designs.
- Further research and development should be conducted to optimize flight envelope protection control laws and design features with emphasis on providing pilot override authority.

6.5 High Speed Upset Recovery

6.5.1 Aircraft With Conventional Flight Controls

For an aircraft with conventional flight controls, pilot authority again is unlimited in the traditional sense, but aircraft protection is also minimal. There is a ramp-up of flight control forces, but no indication when a limit is reached or exceeded. In this case, the pilot is usually given the authority to demand the full aerodynamic capability of the aircraft (limited only by the feel system). However, since commercial airliners usually do not have "g" meters installed, the pilot does not have the ability to maneuver the aircraft with the highest degree of safety. Concern for over stressing the aircraft can actually cause a delay in recovery or cause a sub-optimal recovery to be flown.

Recovery from a high speed upset is straight forward, but dangerous. If flight controls are abruptly applied, the aircraft can be readily overstressed, with possible disastrous results.

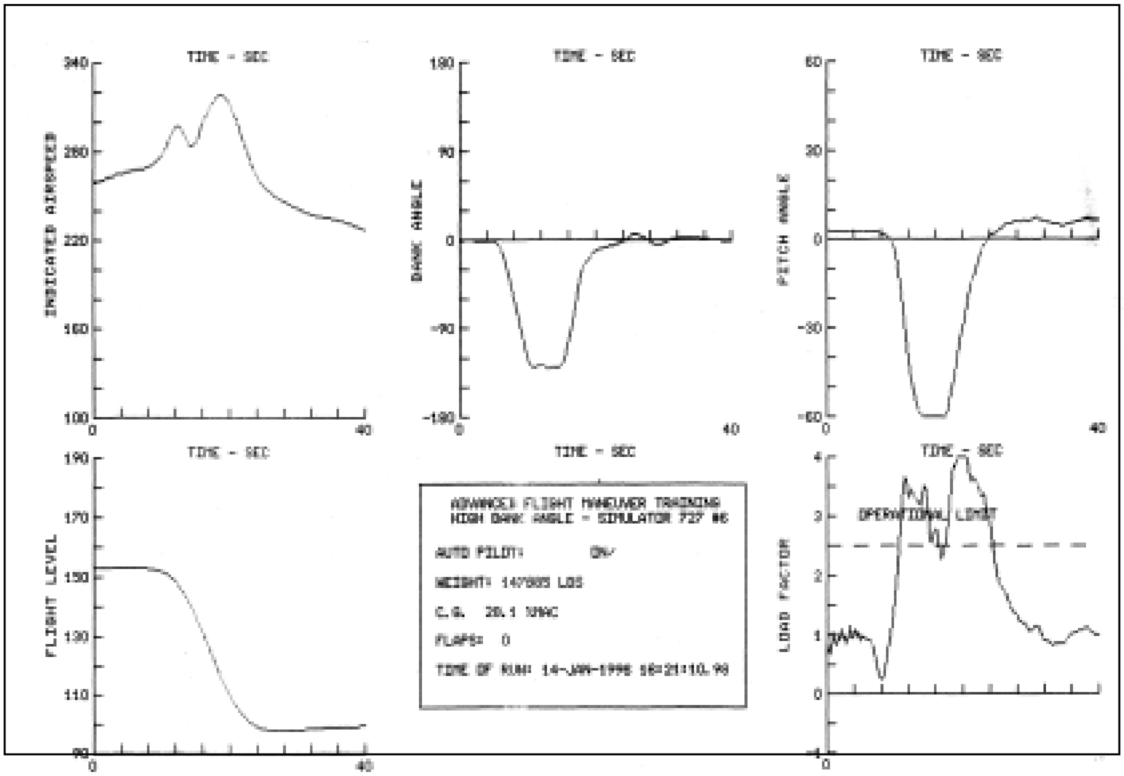

FIGURE 6.1

Figure 6.1 shows a simulator evaluation of a rather severe upset in a B727. The recovery g level peaked at around 3.5 to 4 gs. The altitude lost during the recovery was over 5,000 feet, with a recovery at less than 5,000 feet AGL. If the g available had been limited to 2.5 gs, the altitude loss during the recovery would have been significantly greater and the possibility of terrain contact would have been significantly increased.

6.5.2 FBW Aircraft With "Hard" Protection Features

There have been accidents and incidents where more than the design limit of 2.5 "gs" was needed or used to effect aircraft recovery, from an upset. [14]

There are portions of the flight envelope where the A-320 is aerodynamically capable of pulling more than 2.5 "gs". Flight computer software prevents the aircraft from over g by limiting flight control deflections even when commanded by the pilot (protection limit). The portions of the A-320 flight envelope where more than 2.5 g is aerodynamically possible are shown in figure 6.2.

[14] China Airlines, B747-SP, 2/19/1985, 300 miles NW of San Francisco.

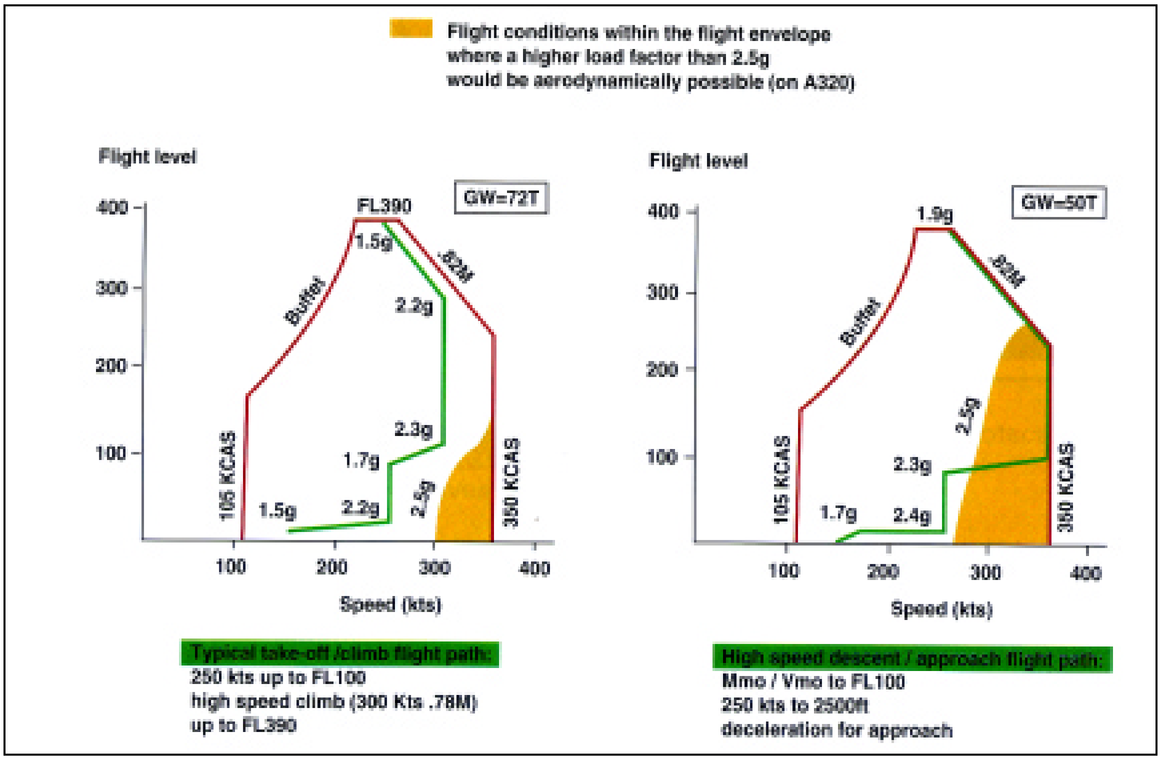

FIGURE 6.2

The "g" limit of an aircraft is typically determined for the maximum takeoff weight, flaps up. For this 2.5 "g" limit, there is a FAR requirement for at least 50% more "g" (3.8 g) available before structural failure.[15] The fuel load and distribution can typically add to the structural integrity an aircraft. The regulations require that an aircraft must have the 2.5 g and 50% safety factor (3.8 g capability) for all fuel loads; from the lightest to the heaviest.

The $W_{equivalent}$ (W_{eq}) of the A-320 at a takeoff gross of 169,750 pounds pulling 2.5 "gs" is 424,375 pounds. Adding the 50% yields a W_{eq} of 636,562 pounds.

$$W_{eq} = nW$$

As weight is reduced, at the end of the flight, the "g" necessary to generate the same Weq structural load is higher, and can be solved by rearranging the above equation.

$$n = W_{eq}/W$$

For a descent weight of 130,000 pounds, "n" now becomes 4.9 "gs." Although this rather basic analysis would appear to yield a higher g capability, there is unfortunately incomplete engineering in this regard. The only required capability of the aircraft for any fuel load is the 3.8 g requirement. The 4.9 g capability is not currently supported by engineering analysis.[16]

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[15] FAR 25.303
[16] Personal conversation Alain Garcia, Senior Vice-President Engineering Airbus Industrie, April 1998.

Although aircraft structural integrity may be compromised by a g load in excess of 3.8 gs, aircraft structural integrity is more severely compromised by terrain impact

Depending on dive angle, this increased “g” capability can result in an altitude loss of almost _ of the 2.5 “g” case. A 4.9 “g” recovery results in a significantly less altitude loss than a 2.5 “g” recovery.

It is conceivable that a fully intact aircraft after an upset could impact the ground pulling 2.5 “gs”, where a little more “g” would have resulted in a successful recovery The pilot in command needs to be given the choice between ground contact or the possibility of an over-stressed aircraft. This can be accomplished while retaining the “g” protection in the Airbus FBW design, with the addition of an over-ride button to “drop” the protections, if the pilot in commands deems such emergency action is necessary.

6.5.3 FBW Aircraft With “Soft” Protection Features

With this design, the pilot is granted full authority limited only by the constraints of the aircraft’s aerodynamic capability and the feel system. If ground contact becomes an over-riding safety consideration, the pilot is allowed to intentionally exceed the design limits.

In the B-777, the pilot is not warned when design limit of 2.5 “gs” is reached. This warning could be implemented through the aircraft’s feel system, or by the use of audio warnings.

6.6 Flight Envelope Protection Conclusions

Both the hard and soft FBW flight control systems afford a higher degree of maneuverability and performance over conventional hydromechanical systems. The soft flight control system affords higher pitch rates and attainable g, and this increased capability results in shorter exposure times below the entry altitude, but not necessarily less altitude lost during the maneuver.

The most effective flight control system would be one that combines the best features of both the current hard and soft flight control system designs. This desired flight control system would then be one that allows the pilot to easily attain maximum allowable aircraft performance (as with the design of current hard flight control systems). However, if the pilot desired increased performance, the hard limits could be over-ridden and full aerodynamic performance could be attained (as is the capability with current design of soft flight control systems). In addition, a g limiting system could be designed that takes into account current weight, Mach, airspeed, and CG, and varies the hard limit accordingly.

7.0 FUTURE TRENDS

Airbus is proposing a 600-800 passenger aircraft, the A3XX. One of the possible additions to the protection scheme is an automatic recovery in case of a GPWS terrain warning. This is a further degradation of pilot authority. To give an automatic system the ability to take control from the pilot and effect recoveries from a possibly false warning without pilot over-ride capability is unconscionable. The argument is that an aircraft with this many people cannot afford to allow the pilots the luxury of delaying the recovery. There have been numerous cases of aircraft receiving a GPWS terrain warning while at high altitude, in a holding pattern[17]. The warning in the holding pattern often results from the radar altimeter locking onto another aircraft. For an aircraft to initiate a climbing recovery in such a situation could be catastrophic. There are many considerations and safety interlocks that must be addressed for such a system to even be considered. There are also human factor issues such as, flight crew reaction when the aircraft starts an abrupt climbing maneuver? Would the crew be startled and perceive this as an autopilot or aircraft malfunction. The issue must be addressed; does this system enhance or decrease safety?

8.0 CONCLUSIONS/RECOMMENDATIONS

The pilot in command is the final authority. The pilot in command is the arbitrator should a conflict arise. Only the pilot in command can make real time, on scene decisions concerning the safe conduct of the flight. To arbitrarily abrogate this legal position of authority and

[17] personal experience of author.

responsibility because of well-intentioned, but flawed design can not be condoned. **It is the position of this committee that a proper protection system must function without restricting the function and command authority of the pilot in command.**

Pilot authority means that the pilot has the ability, if necessary, to access maximum aircraft performance, consistent with safe operation. Flight envelope protection features can form an indispensable part of that authority and these envelope protections features need to be standardized in the industry.

8.1 Conclusions

- Pilot in command authority must not be limited. Desired and appropriate pilot actions must be allowed especially in an emergency situation. What is the desired and appropriate action must be at the final discretion of the pilot.

- Protection schemes need to be properly implemented in aircraft design and the aircraft flight envelope must be appropriately protected.

- Operators of fleets with a mix of conventional and FBW aircraft should reevaluate the benefits of a fleet standard CFIT recovery procedure vs. a FBW aircraft specific procedure that would provide such aircraft with better performance.

- The A320/330 full aft stick CFIT recovery vs 3 deg/sec pull gave better and more consistent performance without any increase in risk of exceeding envelope parameters. No additional or specific pilot training was necessary to perform the full aft stick recovery technique since the FBW design provides excellent pitch rate and g control as well as excellent envelope protection for stall, overstress, or overspeed.

- The evaluation pilots' found that the enhanced flight path control precision and envelope protection features available through FBW design were highly desirable. The evaluation team preferred the flight envelope limiting features ("soft limits") of the B777 design to a "hard limit" design. This was a subjective judgement based on the premise that there may be situations unforeseen by the designers where the pilot might need to achieve full aerodynamic capability as opposed to being software/control law limited. Another approach may be to incorporate "hard limits" with a pilot override capability such as an "instinctive cut-out" switch.

- **The most effective flight control system would be one that combines the best features of both the current hard and soft flight control system designs. This desired flight control system would then be one that allows the pilot to easily attain maximum allowable aircraft performance (as with the design of current hard flight control systems). However, if the pilot desired increased**

performance, the hard limits could be over-ridden and full aerodynamic performance could be attained (as is the capability with current design of soft flight control systems). In addition, a g limiting system could be designed that takes into account current weight, Mach, airspeed, and CG, and varies the hard limit accordingly.

8.2 Recommendations

- To maintain pilot authority over a malfunctioning on-ground sensing system, a method of pilot over-ride must be provided.

- To maintain pilot authority over a malfunctioning stall warning system, a method of pilot over-ride must be provided.

- To maintain pilot authority over the management of engine thrust, reduction of the maximum attainable engine thrust must not be made for merely economic considerations. Although normal maximum available thrust may be set to a particular determined value, a method to over-ride this restriction and obtain maximum thrust available consistent with aerodynamic and controllability issues must be provided.

- Further research and development should be conducted to optimize flight envelope protection control laws and design features with emphasis on providing pilot override authority.

- Research should be conducted on a g limiting system that takes into account current weight, Mach, airspeed, and CG, and varies the aircraft's g capability accordingly.

- A320/A330/A340 operators should use the manufacturers recommended full aft stick CFIT recovery procedure.

- B-777 operators should use the manufacturer's recovery procedure.

Appendix A

Effects Of Additional Thrust On Windshear Recovery

Evaluation of Engine Effects on Takeoff Performance in Windshear using the A-320 Simulator

Harry Walker
United Airlines
17 Jan 1999

I. Overview

This test was conducted as an evaluation of the effects of two different engine models on the performance of the A-320 during the takeoff event with windshear. Of interest was the performance in respect to altitude loss, airspeed decay, and time to climb out of the windshear area. The two different engine models were the PW 2522 engine and the PW 2524 engine.

II. Equipment Description

The evaluation was conducted on the A-320 simulator number one at UAL DENTK. It contained all aero models for the A-320 as well as being fleet representative of the current UAL fleet. The engines were simulated using power management tables (attach 1) for the PW 2522 (V2522-AS) and the PW 2524 (V2524-AS). Simulator engineer Jason Hartman (UAL) incorporated these models into the UAL simulation in lieu of the standard engine models. These new power models were used to simulate the engine configurations of the A-319. The PW 2522 produces approximately 2200lbs of thrust per engine and the PW 2524 produces approximately 2400lbs of thrust per engine.

III. Data Acquisition

F/O Harry Walker (test pilot), Capt. Jef Fleener (previously an A-320 Capt. at UAL), and Capt. Dennis Taylor (UAL 737-300 Capt.) conducted the evaluation. The simulator was placed at a representative gross weight (approx. 160,000 lbs.) and in position on the runway. A normal takeoff was performed and the autopilot was engaged shortly after the gear was retracted. All data were collected using the standard operating procedure as printed in the UAL A-320 flight manual pg. 6-217 (attach 2). Test conditions were standard day, gear up prior to windshear, flaps 1. Windshear models 2 and 4 were used. Model 2 has a windshear event occur at approximately 55 feet AGL. Windshear model 4 has the windshear event occur at approximately 550 feet AGL. Four event sets were flown. Set one with the PW 2522 engine, windshear model 4. Set Two was with the PW 2524 windshear model 4. Set Three was with the PW 2522 engine with windshear model 2. Set Four was with the PW 2524 engine with windshear model 2. Once windshear was detected (start of airspeed loss) the TO/GA button was pushed and the throttles pushed to maximum and held there to eliminate any autotthrottle tendencies to reduce thrust. The autopilot was disengaged, pitch attitude rotated toward 17.5 and SRS guidance was used. Speed brakes were confirmed retracted and flight path was controlled to follow SRS command bars. The simulator windshear recovery-training program automatically generated data at attachment 3.

IV. Findings / Results

During the windshear model 4 events the PW 2522 engine configuration had on average a 495 ft altitude loss, an airspeed loss of 54.5 KIAS, and spent 51.75 seconds in the event. The PW 2524 engine configuration had an average 395 ft loss, an airspeed loss of 41.5 KIAS, and spent 51.25 seconds in the event.

During the windshear model 2 event the PW 2522 engine configuration had on average a 185 ft altitude loss, an airspeed loss of 37.75 KIAS loss and spent 32.5 seconds in the event. The PW 2524 engine configuration had an average 120 ft altitude loss, a 42.75 KIAS loss and spent 34.25 seconds in the event.

	Windshear Model 4		Windshear Model 2	
Averages	PW 2522	PW 2524	PW 2522	PW 2524
Alt Loss	495ft	395 ft	185 ft	120 ft
Airspeed Loss	54.5 KIAS	41.5 KIAS	37.75 KIAS	42.75 KIAS
Time in Event	51.75 Sec	51.25 Sec	32.5 Sec	34.25 Sec

V. Conclusions / Recommendations

The data at attachment three shows the positive effect of extra thrust during windshear recoveries. On average, the aircraft will lose 100ft less, 13KIAS, and spend approximately the same time in the windshear event (0.5 sec delta). As windshear is a random event a direct correlation between each event is not possible but in the aggregate extra thrust increases the aircraft's ability to avoid ground contact in the event of windshear. Increased thrust also reduced the amount of time the aircraft was exposed to the low altitude windshear event. This reduction in time enables the aircraft to gain altitude quicker and thus avoid ground impact.

The amount of difference between the two engine models in recovery altitude and airspeed loss is on the order of 20% of the total loss. The difference between the engine thrust output is on the order of 10%. Thus a small increase in thrust results in a doubling of the safety margin. If increased thrust is available it should be used to increase the safety margin. If the aircraft is structurally able to have an increased thrust engine it should be installed. If the reduced thrust option is desired for cruise cost reasons the pilot should be able to select the higher thrust in an emergency situation. An increase in 20% in the safety margin prior to ground impact is an obvious benefit.

Attachment One
Engine Thrust Models
On File

Attachment Two

UAL Standard Operating Procedures
Excerpt – Ground Proximity Warnings
On File

Attachment Three
Windshear Recovery Data Sheets
On File

<u>Evaluation of Engine Effects on Takeoff Performance in Windshear in the B-777</u>

Harry Walker
United Airlines
28 Jul 1998

I. Overview

This test was conducted as an evaluation of the effects of two different engine models on the performance of the B-777 during the takeoff event with windshear. Of interest was the performance in respect to altitude loss, airspeed decay, and time to climb out of the windshear area with the PW 4000 engine (74000 lbs thrust) and the PW 4084 engine (90000 lbs thrust).

II. Equipment Description

The evaluation was conducted on the B-777 simulator number two at UAL DENTK. It contained all aero models for the B-777 as well as being fleet representative of the current UAL fleet.

III. Data Acquisition

F/O Harry Walker and Mr. Bill Dobbs (DENTK Sims) conducted the evaluation. The simulator was placed at a representative gross weight (approx. 499,500 lbs.) and in position on the runway. A normal takeoff was performed and the autopilot was engaged shortly after the gear was retracted. All data was collected with the autopilot on to eliminate pilot technique from the windshear recovery. Test conditions were standard day, gear up prior to windshear, flaps 5. Two different windshear models were used. Windshear model 2 and 4. Model 2 has a windshear event occur at approximately 55 feet AGL. Windshear model 4 has the windshear event occur at approximately 550 feet AGL. Four event sets were flown. Set One with the PW 4000 engine, windshear model 2. Set Two with the PW 4000 windshear model 4. Set Three was with the PW 4084 engine with windshear model 2. Set Four with the PW 4084 engine with windshear model 4. All events were flown with the autopilot effecting the recovery. Once windshear was detected (start of airspeed loss) the TOGA button was pushed twice and the throttles pushed to maximum and held there to eliminate any autotthrottle tendencies to reduce thrust. The simulator windshear recovery-training program automatically generated data at attachment one.

IV. Findings / Results

During the windshear model 4 events the PW 4000 engine configuration had on average a 380 ft altitude loss, an airspeed loss of 55 KIAS, and spent 13.5 seconds in the event. The PW 4084 engine configuration had an average 200 ft loss, an airspeed loss of 51 KIAS, and spent 12.5 seconds in the event.

During the windshear model 2 event the PW 4000 engine configuration had a 36 KIAS loss and spent 15.5 seconds in the event. The PW 4084 engine configuration had a 34 KIAS loss and spent 11.0 seconds in the event.

	Windshear Model 4		Windshear Model 2	
Averages	PW 4000	PW 4084	PW 4000	PW 4084
Alt Loss	380 ft	200 ft	None	None
Airspeed Loss	55 KIAS	51 KIAS	36 KIAS	34 KIAS
Time in Event	13.5 Sec	12.5 Sec	15.5 Sec	11.0 Sec

V. Conclusions / Recommendations

The data at attachment one shows the positive effect of extra thrust during windshear recoveries. If increased thrust is available to the pilot it should be used to increase the safety margin. As windshear is a random event a direct correlation between each event is not possible but in the aggregate extra thrust increases the aircraft's ability to avoid ground contact in the event of windshear. Increased thrust also reduced the amount of time the aircraft was exposed to the low altitude windshear event. This reduction in time enables the aircraft to gain altitude quicker and thus avoid ground impact.

Attachment One
Takeoff Events with Windshear
B-777 Data Sheets
On File

Evaluation of Engine Effects on Windshear Recoveries in the B-777

Harry Walker
United Airlines
30 Jun 1998

I. Overview

This test was conducted as an evaluation of the effects of two different engine models on the performance of the B-777 during windshear recoveries. Of interest was the performance in respect to altitude loss with the PW 4000 engine (74000 lbs thrust) and the PW 4084 engine (90000 lbs thrust).

II. Equipment Description

The evaluation was conducted on the B-777 simulator number one at UAL DENTK. It contained all aero models for the B-777 as well as being fleet representative of the current UAL fleet.

III. Data Acquisition

F/O Harry Walker and Mr. Bill Dobbs (DENTK Sims) conducted the evaluation. The simulator was placed at a representative gross weight (approx. 445,000 lbs.) and altitude (2000 Ft). All events were flown using the autocoupled approach to a autopilot recovery. Test conditions were standard day, Gear down, Flaps 30, V Ref 141 KIAS, ILS RWN 26 DEN, windshear model number 7. Four event sets were flown. Set One with the PW 4000 engine, recovery at 800 ft RA (radio altitude). Set Two was the same as set one with recovery at the point where airspeed spiked to +15 knots and then returned to V Ref. Set Three was with the PW 4084 engine with recovery at 800 ft RA. Set Four was the same as set three with recovery as in set two. Data at attachment one was automatically generated by the simulator windshear recovery-training program.

IV. Findings / Results

On average the PW 4000 engine configuration had a 233 ft altitude loss with a min airspeed of 97 KIAS during the recovery. The PW 4084 engine had a 185 ft loss with a minimum airspeed of 100 KIAS.

V. Conclusions / Recommendations

The data at attachment one shows the positive effect of extra thrust during windshear recoveries. If increased thrust is available to the pilot it should be used to increase the safety margin. As windshear is a random event a direct correlation between events is not possible but in the aggregate extra thrust increases the aircraft's ability to avoid ground contact in the event of windshear.

Attachment One
Windshear Recovery Events
B-777 Data Sheets
On File

Appendix B

Flight Test Results Of The Controlled Flight Into Terrain Avoidance Maneuver In Fly-By-Wire Transports

I. Abstract

Controlled Flight into Terrain (CFIT) is the leading causes of aviation accidents.[18]

A test program was developed to compare the CFIT maneuver performance capabilities of aircraft with hard versus soft Fly-By-Wire (FBW) flight control systems. To obtain this data, simulated CFIT avoidance maneuvers utilizing a Boeing 777-300 and an Airbus A330-200 were performed. These tests were performed at the Boeing Flight Test Facility in Seattle, Washington and the Airbus Flight Test Facility at Toulouse, France.

This flight test had a two-fold purpose. The first was to evaluate the effectiveness and appropriateness of a recovery technique that was developed for convention aircraft without regard for the flight envelope protections incorporated in modern FBW aircraft. The second purpose was to develop and/or evaluate CFIT escape maneuvers that utilize the maximum capability of the aircraft afforded by the protections incorporated in their respective FBW flight control systems.

As a direct result of this flight-test activity, one major US operator of Airbus aircraft (United Airlines) has changed the CFIT escape maneuver for these aircraft.

II. Introduction

A. Purpose of Flight Test

- To evaluate the effectiveness and appropriateness of a recovery technique that was developed for convention aircraft without regard for the flight envelope protections incorporated in modern FBW aircraft.

- To evaluate and/or develop CFIT escape maneuvers that utilize the maximum capability of the aircraft afforded by the protections incorporated in their respective FBW flight control systems.

[18] CFIT Training Aid, section 3 page 3.3.

B. Ground Proximity Warning Systems

Transport aircraft are equipped with a variety of Ground Proximity Warning Systems (GPWS). These systems will usually, depending upon sophistication, warn the flight crew 5 to 60 seconds before impact. The most advanced system is the Enhanced GPWS that uses a terrain data base and compares current aircraft position to known terrain hazards, contained in an onboard database. This system can provide a full 60 seconds of warning before terrain impact.

C. CFIT Escape Maneuvers

A CFIT escape maneuver is usually performed in response to a GPWS warning and is a procedure designed to remove an aircraft from a pending terrain contact in an expedient manner. This maneuver is designed to remove the aircraft from harm by the use of maximum or near maximum aircraft aerodynamic performance. Typically, the aircraft is in a descent. Upon receiving a terrain warning, the pitch is increased to a value between 15 and 20 degrees nose up until the stick shaker activates or maximum Angle-of-Attack (AOA) is reached. This maneuver can be initiated anywhere from a clean cruise descent (280 to 300 KIAS), to a fully configured condition at approach speed.

An industry task force has recommended the following general GPWS Terrain Warning (CFIT) Escape maneuver.[19]

- React immediately to a GPWS warning
- Positively apply maximum thrust and rotate to the appropriate pitch attitude for your airplane.
- Pull up with wings level to ensure maximum airplane performance.
- Always respect the stick shaker.

The task force report goes on to say:

Studies show that there is little difference in performance between a pull-up rate of 3 degrees/second and 4 degrees/second. Because of this, it is recommended that the standard pull-up rate is 3 degrees/second. [20]

1. AIRCRAFT WITH CONVENTIONAL FLIGHT CONTROLS

[19] Industry task force. Appendix 4-D, section 4-D.1
[20] Industry task force. Appendix 4-D, section 4-D.1.1

The typical CFIT escape maneuver for an aircraft with conventional flight controls, requires the pilot to select TOGA thrust, rotate at a smooth rate of 3 degrees per second (to avoid overstressing or stalling the aircraft) to a pitch attitude of between 15 to 20 degrees nose up. This pitch attitude is maintained until the stick shaker activates or terrain clearance is assured. The stick shaker represents optimum AOA and must be respected to effect recovery. Due to speed and thrust changes, with the resultant variable and usually out of trim stick forces; flying the stick shaker activation angle to maintain optimum AOA, can be quite difficult.

2. FBW AIRCRAFT WITH "HARD" PROTECTION FEATURES

Airbus incorporates "hard" limits in the design of their FBW flight control system. Hard limits prevent the pilot from exceeding the designed flight envelope of the aircraft. That is, the aircraft may not be stalled, over-banked, over-stressed, or over-sped. In other words, the designed aircraft envelope is maintained and protected.

The Airbus design allows the pilot to obtain, in a repeatable fashion, a high level of aircraft performance. However, the pilot may be prevented from obtaining maximum aircraft aerodynamic performance.

The procedure for the CFIT escape maneuver in the Airbus aircraft as recommended by Airbus, is for the pilot to pull full back on the stick and apply TOGA thrust. Speed brakes if extended, will automatically retract.

Control laws either stabilize the AOA at an optimum value or adjust pitch rate to obtain maximum allowed g. With the Airbus CFIT escape maneuver pilots can quickly, easily, and repeatably achieve the maximum level of performance allowed by the envelope limiting system. This ease of handling might, in certain cases, result in optimum CFIT escape performance, even though full aerodynamic performance may not be achieved.

3. FBW AIRCRAFT WITH "SOFT" PROTECTION FEATURES

Boeing incorporates "soft" limits in the design of their FBW flight control system. Soft limits "suggest" and warn when a limit is being approached by increased stick forces and by introducing aural and visual warnings. With soft limits the pilot is warned, but then allowed to stall, over-bank, over-stress or over-speed the aircraft, if necessary or desired.

In a CFIT escape maneuver with the 777, the Boeing recommended procedure (simplified) is for the pilot to immediately select maximum thrust, rotate aggressively to 20 of pitch, and retract the speed brakes.

In all cases, the pitch attitude that results in intermittent stick shaker or initial buffet is the upper pitch attitude limit. When the flaps are not up or at slow speeds with the flaps up, the pitch limit indicator (PLI) provides a visual reference of the pitch attitude limit). Follow flight director TO/ GA guidance if available.[21].

With the Boeing 777 FBW design, maintaining the PLI is less difficult than for conventional aircraft. On most conventional aircraft, the stick forces can be quite high. On the 777 the pilot directly controls pitch attitude and pitch rate. High pitch rates can be attained by the pilot to quickly and precisely place the aircraft at optimum AOA. Although easier than for conventional aircraft, accurately maintaining the PLI still requires a reasonable degree of pilot technique. If ground contact is imminent the pilot can obtain the full aerodynamic performance of the aircraft. High stick forces are required to pull the aircraft into a stall; but the pilot receives numerous warnings and indications of the stall condition. Other than a ramp up of stick force there is not indication that the aircraft's g limit has been reached or exceeded. The authority to obtain maximum g is only limited by the feel system and control power. With this design the pilot is allowed to obtain the maximum aerodynamic capability of the aircraft.

III. Test Plan

A. Test Articles/Locations

For the purpose of this investigation, two aircraft representing the FBW flight control design philosophies under investigation were chosen. The first flight evaluation was conducted using a Boeing 777-300 aircraft at the Boeing flight test facility at Seattle, Washington. The aircraft flight test program was preceded by a work up in a B-777 engineering simulator. The second flight evaluation was conducted using an Airbus A-330-200 aircraft at the Airbus flight test facility in Toulouse, France. This aircraft flight test program was also preceded by a work up in an Airbus A-330 engineering simulator.

Both aircraft were operated at a mid CG with a takeoff weight that would permit the approach CFIT avoidance recovery maneuvers to be preformed at the respective aircraft maximum landing weights.

1. Airbus A-330-200

The A330-200 is a slightly shortened version of the original A330-300. The A330-200 is designed for a typical range of 6,450 nautical miles with a three class passenger load of 381. Normal cruise for the aircraft is .83 to .84 mach with a Mmo of .86 mach. The A330-200 is 193.5 feet long (15.3 feet shorter than the A330-300), 197.8 feet from wing tip to wingtip, and 58.7 feet high. Because of the shorter fuselage, the rudder on the A330-200 needed to be slightly larger (3.5 feet taller). The maximum takeoff gross weight of the A330-200 is 507,100 pounds. For our flight, we weighed 402,600 pounds, just above the maximum landing weight

[21] Boeing 777 Operations Manual, Non-Normal Maneuvers, NNM1.3, February 10, 1995.

of 396,800 pounds. Our fuel load was 134,000 pounds, with a maximum fuel capacity of 250,000 pounds (36,740 US gallons). The two PW 4168 engines are rated at 68,000 pounds of thrust each.

The FBW flight control system utilized in the Airbus design prevents the pilot from stalling the aircraft (an AOA margin is maintained). The aircraft can not be commanded to exceed +2.5 gs or –1 g clean, or +2.0 or 0.0 gs with the flaps extended. The pitch attitude is limited to 30 degrees nose up to 15 degrees nose low. The bank angle is limited to 67 degrees. If the side stick is held full foreword, the speed will stabilize at Vmo +16 knots and Mmo + .04 Mach. The protections can be lost through multiple system failures but, there is no approved or readily discernable method for the pilot to over-ride the flight envelope protections.

2. Boeing B-777-300

The 777-300 is a 33 foot stretch of the 777-200, allowing it to carry 20% more passengers. The maximum take off weight of the –300 is 660,000 with 98,000 pound thrust engines, and maximum landing weight is 524,000 pounds.

The 777-300 has a wheel base of 102 feet and 5 inches, as compared to the 777-200 with a wheel base of 84 feet 11 inches, and the 747-400 with a wheel base of 84 feet 0 inches.

The 777-300 is 242 feet 4 inches long, has a wingspan of 199 feet 11 inches, and a tail height of 60 feet 8 inches. The –300 is designed to carry 350 passengers in a tri-class configuration, with a range of approximately 6500 nautical miles.

For our flight evaluation, we flew the number one 777-300, which has accumulated approximately 500 flight test hours. The aircraft weighed 501,000 pounds, of which 163,500 pounds was fuel. The Rolls-Royce Trent 892 engines were rated at 90,000 pounds of thrust.

The aircraft utilizes a FBW flight control design that does not restrict the pilot from stalling, over-banking, or obtaining the full aerodynamic g capability. The aerodynamic g capability of the 777 can exceed 4 gs under certain conditions of aircraft loading and CG position.

B. Maneuvers/Test Points

1. Simulated CFIT escape maneuvers flown at maximum landing weight and at an approach speed of Vref +5 knots, gear down and flaps at maximum landing setting, at a descent rate of 1500 fpm.
2. Simulated CFIT escape maneuvers flown at typical enroute descent speeds (250 and 300 KIAS as permissible), clean configuration, and a descent rate of 1500 fpm.
3. Aircraft fully instrument and capable of recording at a minimum: α, pitch and Q (pitch rate), NZ, VC, H, and g.

4. Maneuvers to be flown with a smooth pitch rate (target 3 degrees/sec) to a pitch attitude of 17 degrees.
5. Maneuvers repeated with an aggressive (soft protections) respecting the PLI, or full back stick (hard protections).

C. Test Methods

Ron Rogers, APEC Chairman, and three other members of the APEC Committee conducted the 777-300 flight evaluation. The same individuals with the exception of Steve Stowe who was not available, conducted the Airbus A330-200 evaluation. Ron Rogers is a Captain for United Airlines on the A-320. Steve Stowe is a B767 first officer for Delta and a former USAF test pilot. He headed the F-15 Strike Eagle program, and was Vice Commandant of the USAF Test Pilot School. Terry Lutz is an A320 first officer for Northwest, a former USAF Test Pilot School Instructor, and a former project pilot for Calspan Corporation. Joe Kohler is a B747 captain for Northwest and a long time committee member. None of the evaluation pilots were typed in either the B-777 or the A-330 although all the A330-200 evaluators had A-320 type ratings and considerable operational experience in the aircraft.

In preparation for the flight evaluations, work up sessions and test card validations were performed in the respective engineering simulators. Extensive flight evaluations (over 2 hours in the A-330-200 to almost 5 hours in the B-777-300) were conducted in both aircraft. Both the engineering simulators and the test aircraft had extensive data collection capabilities.

IV. Discussion of Results

A. Airbus A330-200

The simulator evaluation was begun with an extensive series of CFIT recovery maneuvers. The objectives were to find what might be the optimum recovery technique, to determine the result of over or under controlling the recovery, and to determine the minimum altitude loss during the recovery. Runs were accomplished in the PA (power approach; gear down and full flaps, except as noted), and Clean (gear and flaps up) configurations, all from a 1500 fpm descent. Recovery was initiated from a callout from the First Officer occurring at 10,000’, with preparatory calls at 200’ and 100’ above the recovery altitude.

AIRCRAFT TEST CARD

Capt Rogers

1. Ground ops and engine start
2. Taxi and ground handling evaluation
3. Normal takeoff at Flex power setting
4. Normal climb to 12,000'
5. CFIT maneuver sequence

Run #	Speed	Config	Max pitch	Pitch rate	Notes
1.	143	Full/Dn	17.5 deg	4 deg/sec	
2.	Repeat			4 deg/sec	
3.	143	Full/Dn	26.0 deg		Full back stick to alpha floor
4.	Repeat				3 deg/sec
5.	170	2/Up	17.5 deg	3 deg/sec	Full speed brakes at entry
6.	170	2/Up	29.0 deg		Full back stick to alpha floor
7.	Repeat				
8.	170	2/Up			Full speed brakes, Full back stick, 1.6g on cockpit meter
9.	254	Clean		3 deg/sec	TOGA
10.	254	Clean		31.0 deg	TOGA/Full back stick/1.8g

FO Lutz

6. Evaluate Dual Input modifications
7. Check roll mode time constant
8. Maximum aircraft performance capability
   - Pull and roll simultaneously (11,000', Flaps 3, 145KIAS, 392,000 lbs)
   - Pull to 10 degrees nose high, then maximum pitch and roll commands (Gear down, Flaps 3)
   - Pull to alpha protections, then apply maximum roll command

9. Simulated engine failure, evaluate aircraft protections

Capt Kohler

10. Approach to stall (15,000', Flaps 1+F, Idle power)
11. Approach to stall (15,000', Gear Down, Flaps Full
12. Normal enroute descent

13. Normal landing (Flaps Full, 500’ lateral offset on final, maneuver at 500’ agl)
14. Simulated engine failure at V1
15. Single engine approach (Flaps 3)
16. Single engine go-around on short final

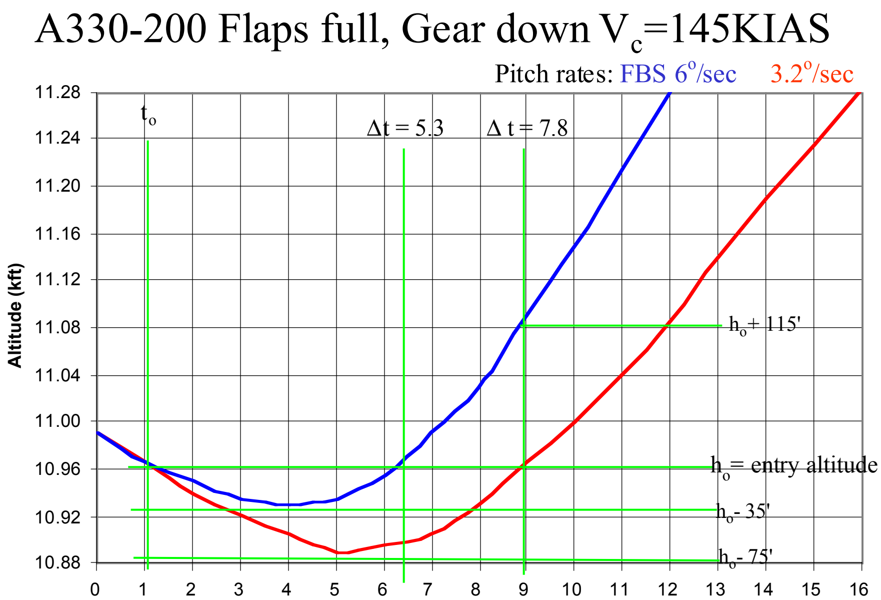
FO Lutz

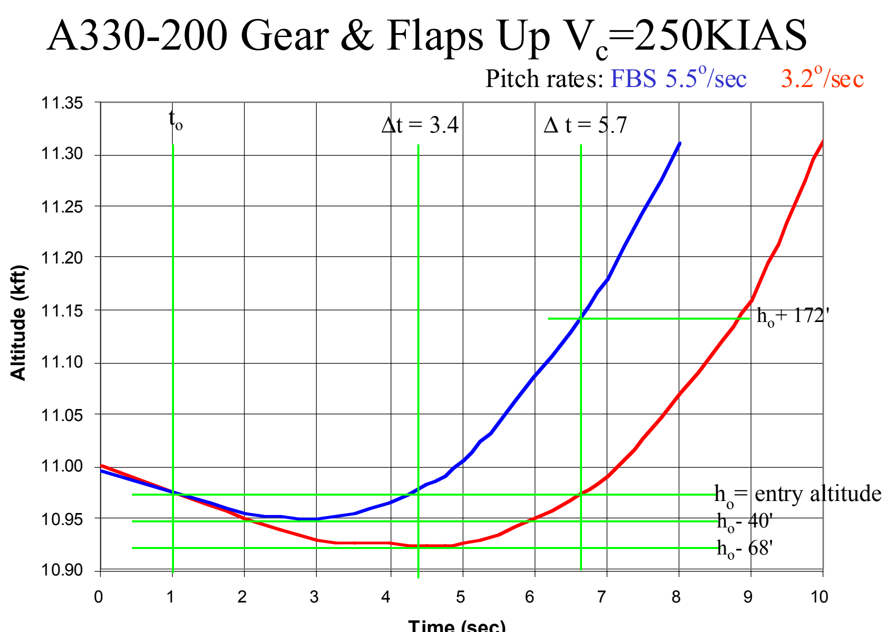
17. Normal landing (Flaps Full, 500’ lateral offset on final, maneuver at 500’ agl)
18. Simulated engine failure at V1
19. Two engine, Direct Law, Flaps 3, manual thrust landing

Capt Rogers

20. Normal landing (Flaps Full, 500’ lateral offset on final, maneuver at 500’ agl)
21. Simulated engine failure at V1
22. Single engine, Direct Law, Flaps 3 landing
23. Full reverse on the good engine during roll out

FLIGHT TEST DATA





Source: Airbus Flight Test Data

Data Plots	Manevuer	Q (°/Sec)	N_z (G)	V_c (Kts)	Δ T (Sec)	Alt Loss (Ft)	Δ Zp V_s (Ft)
4	F/Dn	3.2	1.38	146	7.8	82	-
3	F/Dn (Fbs)	6.0	1.44	145	5.3	52	115 (4)
9	Clean	3.2	1.76	250	5.7	68	-
10	Clean (Fbs)	5.5	1.83	250	3.4	40	172 (9)

A330-200 AIRCRAFT

The benefit of the FBS recovery for the A330-200 in the approach configuration was quite apparent. The use of the full back stick resulted in only a 35 foot altitude loss below the maneuver entry altitude. Whereas, the 3 degree/second rotation rate recovery resulted in a 75 foot altitude loss. More significantly however, the aircraft using the Full Back Stick (FBS) recovery technique was only below the entry altitude for 5.3 seconds, whereas the 3 deg/sec aircraft was below the entry altitude for 7.8 seconds. But most significant was that at the point where the 3 deg/sec aircraft was just getting back to the entry altitude, the FBS aircraft was 115 feet above the entry altitude.

In the clean descent configuration, altitude loss for the FBS recovery was 40 feet, as opposed to 68 feet. The time below the entry altitude was 3.4 seconds as opposed to 5.7 seconds. And finally, the FBS aircraft was 172 feet above the 3 degree/sec aircraft as it was just getting back to the entry altitude.

Pilot Comments

SIMULATOR - Since the iron bird simulator cab is a non-moving cab, it was difficult to make several repeatable runs at a specific pitch rate, notably 3.0 deg/sec. But what was learned from the CFIT maneuvers was that better, more consistent recoveries were achieved by using the Airbus recommended full aft stick technique. They provided the minimum altitude loss, and the maximum climb rate, while minimizing pilot workload. At the completion of the maneuver flown with full aft stick, there was always the feeling of precise pitch control, even though the airplane was recovering from a maximum performance maneuver. The runs flown using the airline AFM recommended “normal pull up to 17.5 deg”, and climbs to SRS (speed reference system) commands, gave more altitude loss and a slower climb. Additionally, the pilot comments indicate that workload actually increases while trying to precisely hold pitch attitude, and several bobbles and pitch overshoots were noted trying to get there. The time spent trying to precisely maintain a pitch attitude could better be used building situational awareness of position and clearance with terrain.

AIRCRAFT - This extensive series of CFIT avoidance maneuvers indicated to us, even without reducing the data, that in the dark absence of situational awareness, the best possible performance is obtained by using a full back stick technique.

Conclusion

The A320/330 full aft stick CFIT recovery vs 3 deg/sec pull gave better and more consistent performance without any increase in risk of exceeding envelope parameters. No additional or specific pilot training was necessary to perform the full aft stick recovery technique since the FBW design provides excellent pitch rate and g control as well as excellent envelope protection for stall, overstress, or overspeed.

Recommendations

A320/A330/A340 operators should use the manufacturers recommended full aft stick CFIT recovery procedure.

B. Boeing B-777-300

SIMULATOR TEST CARD

Following briefings on the B777-300 flight control system, and CFIT avoidance procedures, 2 hours was spent in the simulator cab. This was done mainly for familiarization with switches and controls, to get a basic feel for dynamics and handling characteristics, and to practice CFIT maneuvers that were to be flown in the airplane the following day.

Several CFIT avoidance maneuvers were flown in the simulator cab. There are no hard limits on angle of attack, load factor, pitch rate, and pitch angle in the B777. The evaluation pilots were able to use both the visual display of terrain, and the EGPWS system to set up the maneuvers, and to execute the avoidance maneuvers. Four entries were flown:

1. clean, 300 kts, idle, 1500 fpm descent, smooth pull up
2. clean, 300 kts, idle, 1500 fpm descent, aggressive pull up
3. Vref+5, flaps 30, 1500 fpm descent, smooth pull up
4. Vref+5, flaps 30, 1500 fpm descent, aggressive pull up

The maneuvers were flown toward the simulation terrain, and recovery initiated when the “Pull-up, Pull-up” aural warning was heard. The smooth pull up was flown several times to evaluated what the actual rate was, comparing pitch rate to the g that was produced

AIRCRAFT TEST CARD

Capt Rogers

1. Taxi
2. Takeoff
3. Normal climb
4. CFIT maneuver evaluation:

With the protections fully demonstrated, an investigation into the performance and pilot techniques necessary to get optimum performance during a CFIT avoidance maneuver was begun. A total of seven maneuvers were flown, with the parameters as follows:

1. clean, 300 kts, 1500 fpm descent result: 1.5 deg/sec pull, 1.4g
2. clean, 300 kts, 1500 fpm descent result: 3.5 deg/sec pull, 1.8g
3. clean, 300 kts, 1500 fpm descent result: 4.9 deg/sec pull, 2.2g
4. clean, 300 kts, 1500 fpm descent result: 6.0 deg/sec pull, 2.25g
5. flaps 30, 149 kts, 1500 fpm descent result: 4.8 deg/sec pull, 1.6g
6. flaps 30, 149 kts, 1500 fpm descent result: 4.0 deg/sec pull, 1.6g
7. flaps 30, 149 kts, 1500 fpm descent result: 7.6 deg/sec pull, 1.7g

FO Stowe

5. Dynamics eval, 15,000'/250 kts, in Normal and Direct
6. Stalls (clean, PA)
7. Manual override of the autopilot from a trimmed PA configuration

FO Lutz

8. Clean stall
9. Turning stall (flaps 5, 30 degrees bank)
10. Evaluate trim characteristics (effectiveness, precision to hold speed)
11. Dynamics (s.p., phugoid, roll mode time constant, dutch roll), max L/D
12. Descent for landing at Moses Lake
13. Direct law landing, flaps 20
14. Normal landing from a 1200 ft offset, sidestep at 500 ft
15. V1 cut on the go, clean up on downwind

FO Stowe

16. Normal landing, capture 6 degrees after TD
17. Normal landing from 1200 ft offset, flaps 20

Capt Rogers

18. Normal landing from 1200 ft offset, V1 cut on the go
19. SE pattern, landing

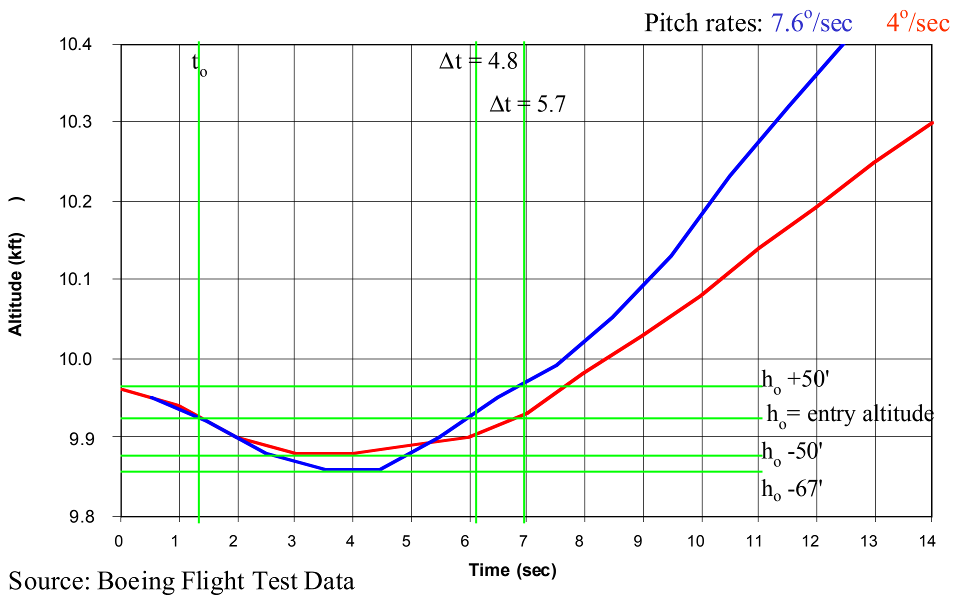
Capt Kohler

20. Normal full-stop landing, delay TD to Vref-5, full thrust reverse on upwind engine
21. Taxi evaluation on narrow taxiways
22. Normal takeoff, V1 cut on the go, SE pattern and landing
23. Climb to FL 350, accel to .86 mach, evaluate noise
24. Slow to 250 kts at altitude
25. Descent to 11,000 ft in Direct Law

Capt Rogers

26. Flight on RAT only for hydraulic power
27. Normal landing at Boeing Field

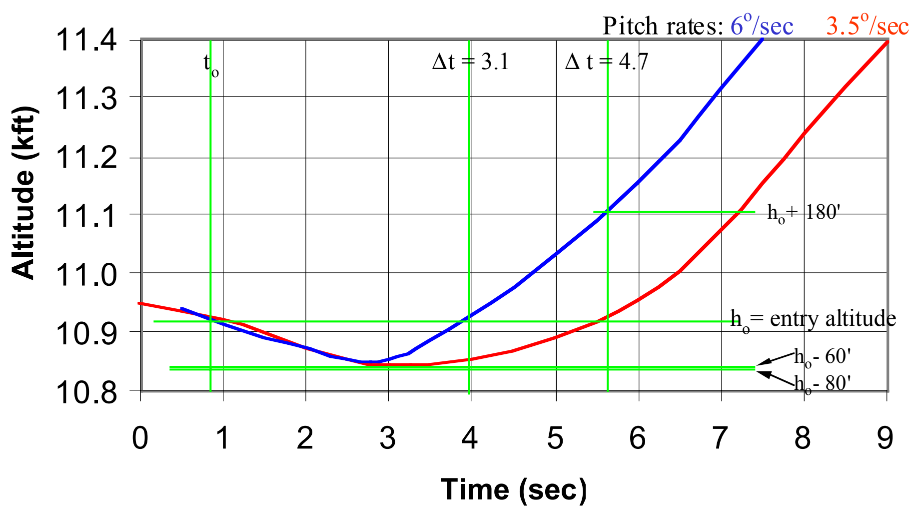
B777-300 Flaps 30° Gear Down V_c=150 KIAS



Source: Boeing Flight Test Data

FLIGHT TEST DATA

B777-300 Gear & Flaps Up - 300 KIAS



Data Plots	Manevuer	Q (°/Sec)	N_z (G)	V_c (Kts)	Δ T (Sec)	Alt Loss (Ft)	Δ Zp V_s (Ft)
15	30F/DN	4.0	1.6	150	5.7	50	-
16	30F/DN®	7.6	1.7	150	4.8	67	50 (15)
11	CLEAN	3.5	1.8	300	4.7	80	-
13	CLEAN®	6.0	2.25	300	3.1	60	140 (11)

777-300 AIRCRAFT

For the B777-300 in the landing configuration, the aircraft with the rapid rotation rate initially performed worse. This was in contrast to the simulator data that showed improved performance. A rapid rotation led to a greater altitude loss during the maneuver, 67 feet versus 50 feet. The exposure time below the entry altitude was still less, 4.8 sec vs 5.7 seconds. But, the aircraft with the rapid rotation was only 50 feet above the aircraft with the normal rotation rate, as it was just returning to the entry altitude**.** The aircraft with the rapid rotation rate did achieve greater altitude gains as the climb continued.

For the enroute descent case, a rapid rotation resulted in a 60 foot altitude loss versus 80 feet for the normal rotation rate. The time below the entry altitude was 3.1 seconds versus 4.7 seconds. And, the aircraft with the rapid rotation rate was 140 feet above the normal rotation rate aircraft as it returned to the entry altitude.

Pilot Comments

SIMULATOR - Pulling smoothly at the standard 3 deg/sec did not produce enough g for maximum performance. Pulling at 6 deg/sec to 20 degrees of pitch provided 1.6g to 2.0g in the simulator. If pull-ups were made more aggressively, pitch attitude would overshoot into the 25 to 30 degree nose high range, and there were several pitch oscillations noted.

AIRCRAFT - Different entry g levels were evaluated, pulling up to a target pitch attitude of 17.5 degrees. At the higher g levels, precisely matching the pitch attitude at 17.5 was difficult, and would often result in a pitch overshoot of 2-3 degrees. The best run appeared to be run 3, where at the end of the run, pitch was exactly at 17.5 degrees, which was right at the pitch limit indicator (PLI), which is the threshold for stick shaker activation. Minimum altitude loss below the pull up altitude (10,000 ‘) was observed to be about 100 feet on run 3. On run 7, a near maximum performance pull up to 30 degrees nose high was executed, activating the stick shaker. The airplane stagnated in climb at 10,900’ and 105 kts with full thrust. While this run gave the maximum initial pitch rate, it bled off energy rapidly, resulting in complete loss of climb performance after a 900’ altitude gain. During all of these maneuvers, maximum thrust was applied at the beginning of the pull up. It nominally took 3-4 seconds for the engines to come to full thrust, which usually occurred at about 15 deg nose during the maneuver.

Conclusions

The evaluation team preferred the flight envelope limiting features ("soft limits") of the B777 design to a "hard limit" design. This was a subjective judgement based on the premise that there may be situations unforeseen by the designers where the pilot might need to achieve full aerodynamic capability as opposed to being software/control law limited.

V. Lessons Learned

A. Simulation

1. The use of an engineering simulator was beneficial in developing recovery techniques and assessing the ability to perform the recovery maneuver without overstressing the aircraft. This was very necessary in the build up phase to avoid or assess the potential for damage to the test aircraft.
2. The use of fixed based simulators did not provide any motion cues and thus was not a true simulation of the dynamics of the aggressive maneuvers being tested or developed. A "quick look" evaluation was performed with a full motion Airbus A-320 and a Boeing 777 simulator at the United Airlines Flight Center, but these simulators did not have the necessary data acquisition capability required for the test program.

B. Aircraft Flight Test

1. It was difficult to consistently obtain a pitch rate of 3 degrees/second over a variety of airspeeds without considerable practice and finesse (both aircraft have a long moment arm and there is no cockpit indication of pitch rate). The pitch rate attained at higher airspeeds (250 to 300 KIAS) tended to be underestimated by the pilot. The evaluation pilots felt that specifying a pitch rate of 3 degrees/second for line operations without a parameter display is impractical. The motion cues and g onset rates played a very important role in the closed loop performance.
2. Flight time to perform the evaluation was very limited. Because of this, detailed coordination preplanning and performance were required to achieve the test objectives.
3. Some of the coordination was international and this contributed to the communications difficulties. Some final issues could only be raised and resolved face to face and this resulted in some significant, last minute changes to the test card.
4. Flexibility in the test was required since our evaluators had limited control of the aircraft configuration and test cards.

5. Last minute test constraints due to structural safety concerns raised during the flight briefing required last minute modifications to the test cards. Care had to be taken to maintain like maneuver comparisons in spite of last minute maneuver modifications.

C. General

1. Manufacturer and FAA test pilots and purchasing company management pilots have traditionally evaluated most aircraft. The Airline Pilots Association has played more of a minor role in such evaluations until recently. Members of ALPA's APEC Committee have evaluated virtually every transport aircraft in current use or development and bring this broad aircraft knowledge along with considerable operational experience to the evaluation process. As a result of APECs evaluation of the CFIT recovery procedure for FBW aircraft, one major US airline, United Airlines, has changed their CFIT recovery procedure.
2. New aircraft should require an OT&E phase where old procedures are evaluated in light of new technological features. This may prevent the application of outdated Standard Operating Procedures that are not in keeping with the benefits derived from system improvements and advancements, such as FBW flight control systems.

VI. Conclusions/Recommendations

From the data gathered in the evaluation, there was not a distinct advantage of the B777 soft limits vs the A320/330 hard limits for CFIT recovery open loop performance.
However, closed loop evaluations showed that the pilots could achieve more consistent performance results as well as achieve target pull out parameters more quickly in the A320/330 than the B777. Even with the B777 soft limit features, pilots were able to use abrupt pitch inputs without fear of overstress or stall. Both aircraft types offered better handling during CFIT recoveries than conventional aircraft since the FBW design features allowed the pilot more precise control of pitch rate and g onset rate than with conventional flight controls.

RECOMMENDATION: Operators of fleets with a mix of conventional and FBW aircraft should reevaluate the benefits of a fleet standard CFIT recovery procedure vs. a FBW aircraft specific procedure that would provide such aircraft with better performance.

The A320/330 full aft stick CFIT recovery vs 3 deg/sec pull gave better and more consistent performance without any increase in risk of exceeding envelope parameters. No additional or specific pilot training was necessary to perform the full aft stick recovery technique since the

FBW design provides excellent pitch rate and g control as well as excellent envelope protection for stall, overstress, or overspeed.

RECOMMENDATION: A320/A330/A340 operators should use the manufacturers recommended full aft stick CFIT recovery procedure.

The evaluation pilots' found that the enhanced flight path control precision and envelope protection features available through FBW design were highly desirable.

RECOMMENDATION: Incorporation of similar FBW design features is highly desirable in future designs.

The evaluation team preferred the flight envelope limiting features ("soft limits") of the B777 design to a "hard limit" design. This was a subjective judgement based on the premise that there may be situations unforeseen by the designers where the pilot might need to achieve full aerodynamic capability as opposed to being software/control law limited.

Another approach may be to incorporate "hard limits" with a pilot override capability such as an "instinctive cut-out" switch. Or alternately, the CFIT recovery capability on the 777 could be enhanced if the aircraft's Primary Flight Computers (PFC) were design to recognize aggressive pilot inputs as a desire for maximum aircraft performance. The PFCs would then provide maximum pitch rate consistent with AOA or g limits (depending on airspeed). If the resultant aircraft performance was not sufficient, the pilot could then pull to the full aerodynamic capability of the aircraft. Additionally, automatic speed brake retraction, in the event of a go around or CFIT escape maneuver, should be provided in the 777 design. This system although somewhat complex mechanically, can be implemented since the PFCs will control any undesired pitch excursions.

RECOMMENDATION: Further research and development should be conducted to optimize flight envelope protection control laws and design features with emphasis on providing pilot override authority.